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Historical trends and the long-term changes of the hydrological cycle components in a Mediterranean river basin

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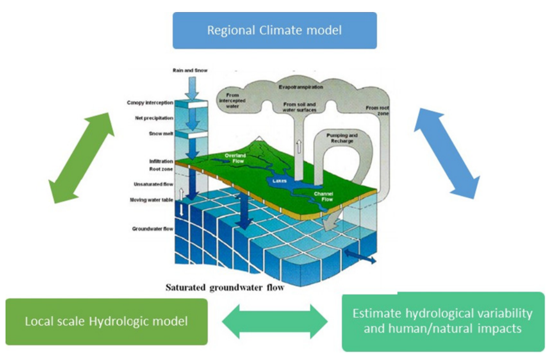
HIGHLIGHTS

- Identifying past long-term hydrologic trends in a Mediterranean river basin using regional climatic and hydrologic models
- Studying the hydrologic trends over the last 4 centuries emphasizing on human and natural forcing
- Identifying the impacts of recorded volcanic activity on the atmospheric and hydrologic conditions over the period 1660-2016

GRAPHICAL ABSTRACT



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ABSTRACT

Identifying the historical hydrometeorological trends in a river basin is necessary for understanding the dominant interactions between climate, human activities and local hydromorphological conditions. Estimating the hydrological reference conditions in a river is also crucial for estimating accurately the impacts from human water related activities and design appropriate water management schemes. In this effort, the output of a regional past climate model was used, covering the period from 1660 to 1990, in combination with a dynamic, spatially distributed, hydrologic model to estimate the past and recent trends in the main hydrologic parameters such as overland flow, water storages and evapotranspiration, in a Mediterranean river basin. The simulated past hydrologic conditions (1660–1960) were compared with the current hydrologic regime (1960–1990), to assess the magnitude of human and natural impacts on the identified hydrologic trends. The hydrological components of the recent period of 2008–2016 were also examined in relation to the impact of human activities. The estimated long-term trends of the hydrologic parameters were partially assigned to varying atmospheric forcing due to volcanic activity combined with spontaneous meteorological fluctuations.

1. Introduction

The Mediterranean region due to its morphology and geographical location is characterized by a complexity in the interactions among the various components of the hydrological cycle (Lionello et al., 2012; Peixoto et al., 1982). Located between the subtropical zone to

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the south and the temperate zone to the north, the climate of the Mediterranean is affected by the arid climate of North Africa and the temperate and rainy climate of central Europe, and the interactions between mid-latitude and tropical processes (Giorgi and Lionello, 2008). This makes the specific area vulnerable to even relatively minor modifications of the general circulation and eventually climate changes, as induced by human activities and interventions, such as the increase of greenhouse gases concentrations and land use changes (Giorgi and Lionello, 2008; Mariotti et al., 2002).

Adaptation and mitigation to climate change entail the interpretation of human - environment interactions to understand the functioning of the system and the naturally imposed from the human induced changes (Dearing et al., 2006). One of the main tools for understanding climate processes prior to systematic human influence on the global atmosphere that begun with the industrial revolution, is historical climatology (Brázdil et al., 2005), which is defined as the study of the past climate before the establishment of modern networks of meteorological measurements (Mauelshagen, 2014). Research in historical climatology is mainly based on analytical techniques such as documentary evidence, corals (Evans et al., 2002), tree rings (Haines et al., 2016), ice cores (Thompson et al., 2013), speleothems, marine, lake, and other sediments (Lintern et al., 2016), soils and landforms (Brázdil et al., 2010; Brázdil et al., 2005). The study of the past alone, although important, cannot ensure the successful management of an integrated human - environment system. It is important to link the past to the present and extent this relationship to include the future, under a more holistic approach that allows an integrated, transdisciplinary synthesis and a much longer time perspective (van der Leeuw et al., 2011). Nevertheless, the limited availability of continuous, homogeneous and quantitative high-resolution observations obstructs this effort (Brázdil et al., 2005). An important tool towards this direction is the reconstruction of climate variations during the last few hundred years using climate models (Brázdil et al., 2010; Brázdil et al., 2005). Such an effort was carried out under a relevant project (SO&P - Simulations, Observations & Palaeoclimatic data), where the multiproxy reconstructions on continental and regional scales for European land areas of climate variations for the period 1500–2000 CE were performed using two state-of-the art GCM (General Circulation Model) climate models (Luterbacher et al., 2004; Pauling et al., 2006; Osborn and Briffa, 2006).

In the present effort, an integrated hydrological model, fed with the time-series reconstructions from SO&P project, has been applied in the Spercheios River Basin in Central Greece (Mediterranean) to examine the historical climatological trends since the 17th century and the associated changes of the hydrological cycle components. The main objective is to identify the magnitude of influences due to human activities (land use changes and engineering alterations in the basin river network) on the hydrological cycle of Spercheios River Basin by comparing the period before and after human interventions, over the last four centuries. The final objective of this effort is to introduce an alternative approach to the challenging field of water management, through the better understanding of how human interventions and climatic variations affect river catchments.

On a global scale, former studies also investigated changes in the hydrological cycle and their driving components for different areas and time periods. An important question is in how far changes in external forcings, such as solar, volcanic, greenhouse gases and land use might be impacting on changes in the hydrology. Specifically, for streamflow the study of Iles and Hegerl (2015) investigated the response of large river basins on strong volcanic eruptions. There are physically plausible, albeit weak signals in the relevant hydrological responses for the major river systems, for instance related to a decrease in the streamflow of the Nile River. For other river basins, the response might be different depending on the impact of the volcanic forcing on the precipitation over the study area. Moreover, in this case, the input climate data stem from reconstructions based on empirical data. This is an important aspect since Regional Climate Model (RCM) studies in the paleoclimatic context are usually related in a statistical sense (in terms of Probability Distribution Functions) to the real climate. The exact temporal evolution of an area, using RCMs driven by large scale General Circulation models, cannot be reproduced accurately due to the high complexity of land-atmospheric interactions that are not considered adequately in these models. Therefore, in this study a relatively high-resolution data set (0.5°. lat × lon) based on empirical data has been used warranting a reasonable good estimation and reconstruction of the real climate trajectory (Pauling et al., 2006).

2. Methodology

2.1. Study area

Spercheios River is located at the central part of Greece (Fig. 1a), it has a total length of approximately 91 km while its annual average discharge fluctuates from 12.9 to 21.6 m^3/s. This high intra-annual variability that can be partially assigned to the summer low flows was caused by irrigation abstractions. The Spercheios River Basin covers an area of 1661 km^2 and has a mean altitude of 641 m (Mentzafou et al., 2015).

Spercheios River's wider area, has been inhabited since the Early Neolithic period due to its strategic location as a crossroad of invaders and trade routes, the fertile soil of the riparian zone, the abundance of freshwater, the existence of the sea at the east, and the mild climate conditions (Tselika, 2006). The basin has been subjected to many hydromorphological changes mainly due to tectonic and sediment erosion-depositional processes (Kraft et al., 1987) that caused multiple alterations in the river's course during the last 2600 years. Based on old maps, historical documentation and archives, at the end of 16th and the beginning of 17th century two main rivers (Spercheios and Mavroneri rivers) run along the valley under study (Cantelli, 1684; Lucas, 1714; Mercator, 1600). Spercheios River flown into Maliakos Gulf at the north part of the basin near Lamia City, while a lake of considerable size (Eropoli) existed along a tributary of Mavroneri River (Fig. 1b).

Pococke (1745) mentioned that Spercheios River, in 1740, was located at the north part of the basin. He also witnessed an earthquake in 1758, estimated as of ML = 6.5 magnitude on the Richter scale (Papazachos and Papazachou, 1989) that could be responsible for the alteration of the river course from the northern to the southern part of the basin, near Thermopyles (Psomiadis, 2010). At the mid–end of the 18th century and beginning of 19th century, Spercheios River flows at the southern part of the basin, while three lakes are located inside the basin. Moreover, there are evidence of irrigations and artificial canals existence at that time (Arrowsmith, 1819; Gell, 1819).

At the end of the 19th century the course of Spercheios River changed route again towards the central part of the basin, which is still partially active, until today. This alteration is attributed either to the great flood of 1889 that caused the failure of the river's embankments, or to the earthquake of ML = 7.0 magnitude on the Richter scale (Papazachos and Papazachou, 1989) that occurred 30 km southeast of the study area in 1894 (Psomiadis, 2010), and/or to the land reclamation projects (Tziavos, 1977). During the late 19th–mid 20th century the main changes in Spercheios hydrography concerned the creation of a more complicated network of irrigation and flood control channels. In 1944 a large ditch close to Lamia city was constructed to drain a major stream (Xerias) and the downstream area of Spercheios River Basin. In 1957–58, Spercheios River was diverted through a flood relief channel that was constructed at the northern part of the basin while many minor projects including river bank stabilization, slope erosion control, canalisation stream dredging and drainage canals construction took place during the last 150 years in the entire hydrographic network of the basin (Mentzafou et al., 2015; Sotiropoulos, 2003). These engineering interventions are responsible for the alteration of the water and sediment balance at the coastal zone and have led to the creation of a new deltaic system at the northern part of the

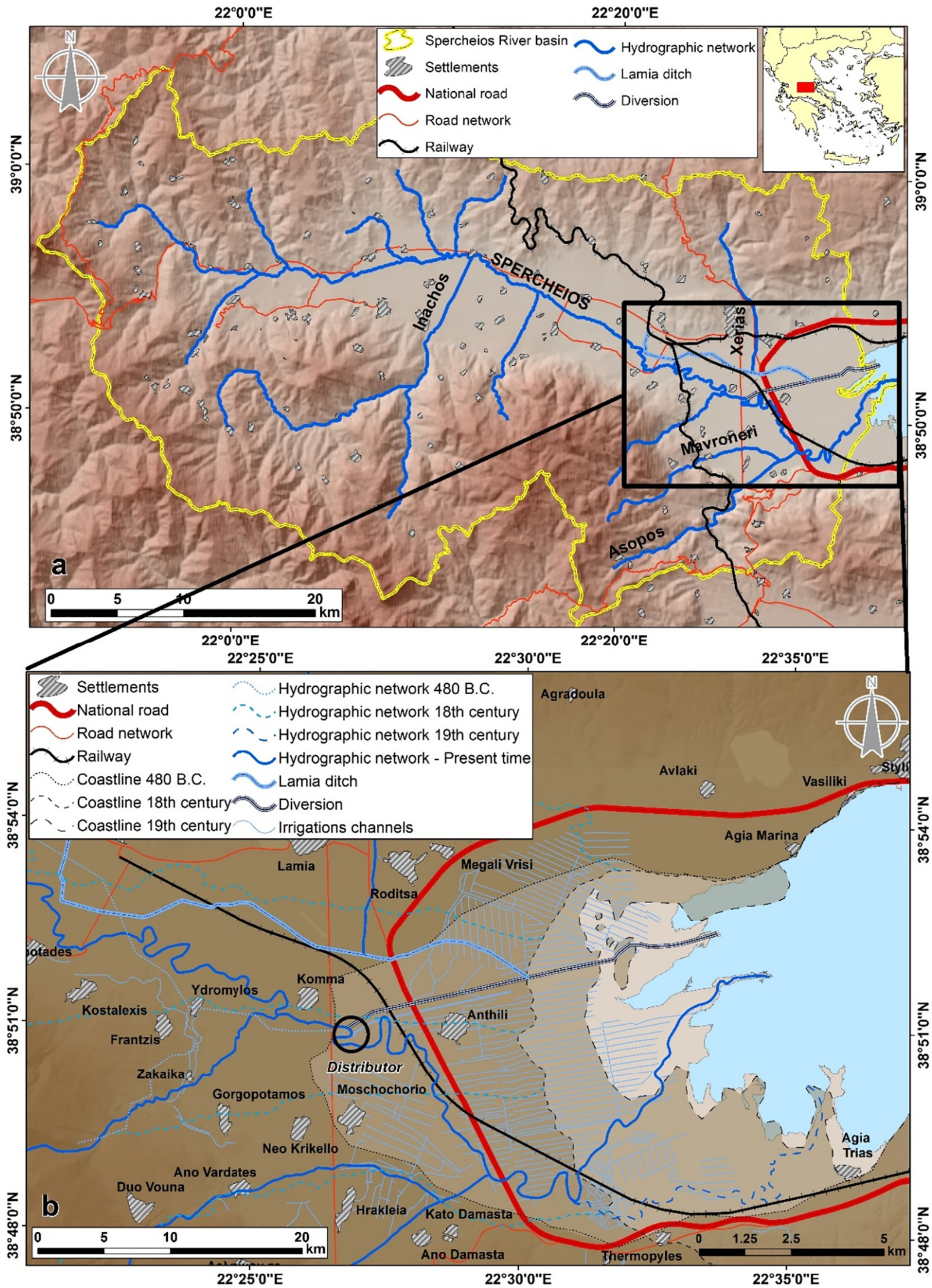

Fig. 1. (a) Current state of the study area and (b) hydromorphological changes at Spercheios River mouth wider area since the 17th century. Coastline 480 BCE: From Psomiadis (2010), based on "Charta of Greece" by Rigas Feraios (Vienna, 1797). Coastline 18th century: based on "Carte de la Locride où sont les Thermopyles" by Barbié du Bocage (1782). Coastline 19th century: based on "Carte de la Grèce rédigée et gravée au Dépôt de la Guerre d'après la triangulation et les levés exécutés par les officiers du Corps d'Etat-Major à l'échelle de 1/200 000" by Gillot (Paris, 1852).

estuary as well as a decrease in the rate of advance, or even a retreat, in the coastline at the southern part - old delta (Pechlivanidou, 2012; Psomiadis, 2010; Fig. 1b).

Concerning the long-term alteration of land use in Spercheios River Basin, based on historical documentation and archives, the most common cultivations in 1570 were cereals, wheat, barley, oats, millet, pea, vines, cotton, flax, anise and vegetables (Kabrda, 1962). In the early 18th century vegetable, fruits gardens and groves were cultivated in the area (Lucas, 1714). In the early 19th century, two artificial irrigation canals existed, which provided water from Spercheios River to the extensive rice grounds, grain, tobacco, and cotton cultivations (Dodwell, 1819; Holland, 1815; Leake, 1835). During the Greek War of Independence in 1821–1833 and until 1835 the area was abandoned. The next records of agricultural activities in the area commence in 1840 (corn,

tobacco and cereals) and in 1852 (cereals, rice, sesame, cotton, tobacco, Stavropoulos, 2013). Nowadays, mainly cereal, cotton, legumes, sugar beets, rice and olive trees are cultivated in the area based on data provided by Greek Payment Authority of Common Agricultural Policy Aid Schemes - OPEKEPE.

2.2. Historical climate data

The long-term changes of the water balance components in Spercheios River Basin have been examined by providing in a hydrological model, the necessary past meteorological data (years 1660–1990). These data were retrieved from a gridded, high-resolution (0.5° longitude ∗ 0.5° latitude), monthly mean precipitation and surface temperature reconstructions over the last 500 years for the European region (Simulations, Observations & Palaeoclimatic data: climate variability over the last 500 years, FP5-EESD - Programme for research, technological development and demonstration on "Energy, environment and sustainable development, 1998-2002", EVK2-CT-2002-00160 SOAP; Luterbacher et al., 2004; Pauling et al., 2006). The main concept of the reconstruction technique is the Principal Component regression analysis (PCR). The rationale is to calibrate the most important patterns of temperature and precipitation variability (Empirical Orthogonal Functions, EOFs) with observational data. Eventually the calibrated data were validated for a period (excluded in the calibration and validation metrics) and were calculated for the gridded data sets to assess the robustness of the reconstruction. In a last step the validated PCR models were used to extend the reconstruction further back in time using proxy data e.g. tree rings or historical meteorological readings. From these two data sets, near-surface temperatures and precipitation were retrieved for the point co-located with the study area (latitude 38.87°N, longitude 22.24°E) for the hydrological modelling. It should be noted that due to the specific resolution of the reconstruction, it was not possible to retrieve more than one time-series in the study area. Further details of the climatic reconstruction technique can be found in the studies of Luterbacher et al. (2004) and Pauling et al. (2006).

To examine the good performance of the GCM from SO&P project in the specific area, the reconstructed time-series were compared with actual measurements for the common operating period. More specifically, the comparison was performed between the reconstructed monthly precipitation and temperature time-series of the past and Lamia meteorological data (Hellenic National Meteorological Service, WMO 16675; latitude: 38° 52′ 35″ N, longitude: 22° 26′ 09″ E) for the common operating period (1970–1998 for precipitation and 1970–1990 for temperature). The specific meteorological station has been selected for this comparison due to its availability of data prior to 1990 and its credibility as part of the WMO network. The criteria used to investigate the time-series compatibility were: mean error *ME*; mean absolute error *MAE*; root mean squared error *RMSE*; standard deviation of the residuals *STDres*; correlation coefficient *R*; and percent bias *PBIAS*.

2.3. Hydrological simulation

2.3.1. Modelling tool

The modelling tool used in this effort is MIKE SHE, developed by the Danish Hydraulic Institute Water and Environment (DHI, 2014). MIKE SHE is a physically based distributed model that is able to simulate all hydrological domains within the land phase of the hydrological cycle, in a river basin. MIKE SHE is fully integrated with the channel - flow code MIKE 11, which is a one-dimension model that can simulate water flow and level, water quality and sediment transport in rivers, flood plains, irrigation canals, reservoirs and other inland water bodies (DHI, 2014). The specific hydrological model has already been successfully set up, calibrated and validated during recent research efforts for Spercheios River Basin (Mentzafou et al., 2017).

More specifically, during a past research effort, the hydrological model of Spercheios River Basin was set up and calibrated for the hydrological years 2008/2009–2010/2011 and validated (at a daily resolution) for the hydrological years 2013/2014–2014/2015 (Mentzafou et al., 2017). These periods were chosen based on the data availability (actual in situ measurements of water level and discharge and high quality climatological data) and on the fact that in 2008 the last engineering flood control structures in the hydrological network and the river banks were completed. Based on the results of Spercheios River Basin hydrological model calibration, there is a satisfactory agreement between observed and simulated water levels and discharge. Their correlation coefficient *R* can be characterized as moderate to high, and in all cases the data are statistically significant at the 0.05 level, indicating the sufficient performance of the model. During validation, the resulted correlation coefficient *R* was also moderate to high, and the data were also statistically significant at the 0.05 level. The model simulation can be considered satisfactory since the results meet with the criteria proposed by Moriasi et al. (2007; $R2 > 0.50$, $RSR < 0.70$, and PBIAS $\pm 25\%$ for streamflow) in all simulation cases (Mentzafou et al., 2017).

In order to investigate the historical trends of the hydrological cycle components, the aforementioned model of Spercheios River Basin was run for the hydrological periods of 1660/61–1900/01 in natural conditions, after omitting water abstractions and all anthropogenic interventions in the river network (e.g. small weirs, distributor) and of 1960/61–1989/90 taking into consideration all the human engineering alterations at the river network. The period of early–mid 20th century was not possible to be included in the simulation, due to the major engineering interventions (irrigation and flood control channels, drainage ditches, Spercheios River's diversion, canalisation) that took place within a relatively short period of time and caused continuous changes in the dominant water management practices of the area. Thus, to confirm the effect of the water management projects on the hydrological cycle components, the model was also run for the period 2008/09–2015/16, during which the most recent water management infrastructure and practices were known and stable. The model run, first with and then without considering the irrigation system of the basin (irrigation channels, boreholes, wells), and the water flow regulation projects (weirs, distributor) and a comparative assessment followed to indicate the human impacts on the current hydrologic regime.

2.3.2. Climatological data

The meteorological data necessary for the hydrological modelling were retrieved, as mentioned above, from SO&P: Climate reconstructions (Pauling et al., 2006) for the periods 1660/61–1900/01 and 1960/61–1989/90 and included average monthly precipitation and temperature. For the period 2008/09–2015/16 detailed and high quality climatological data were available from Makrakomi meteorological station (National Observatory of Athens; latitude: 38° 56′ 13″ N, longitude: 22° 07′ 03″ E; http://penteli.meteo.gr/stations/makrakomi/) and included precipitation and average, maximum and minimum temperature on daily basis.

Due to lack of detailed meteorological data for the entire period under study, the use of the Penman-Monteith equation or Hargreaves method for the estimation of potential evapotranspiration (*PET*) was not possible. Additionally, Thornthwaite method is considered to underestimate potential evapotranspiration in Greece (Koutsoyiannis and Xanthopoulos, 1999). Therefore, *PET* was estimated based on a parametric, radiation-based model, which is the simplification of the Penman-Monteith formula by introducing three regionally varying parameters and which is parsimonious both in terms of data requirements and number of parameters (Tegos et al., 2015; Tegos et al., 2013). The mathematical expression of the parametric model for every time step is the following: $PET = \frac{aR_a - b}{1 - cT}$, where, PET potential evapotranspiration (mm), Ra ($\mathrm{KJm^{-2}}$) is the extraterrestrial shortwave radiation calculated without measurements, a ($\mathrm{KgKj^{-1}}$), b ($\mathrm{Kgm^{-2}}$) and c ($\mathrm{C^{-1}}$) are the

calibrated parameters, while T (°C) is the mean air temperature (Tegos et al., 2015).

MIKE SHE model can only handle daily time-series and therefore monthly climatological time-series had to be disaggregated. It should be noted that the model's results were again aggregated and the final statistical tests were performed in annual time step (in the case of water budget) or monthly (in the case of discharge) while in all the other cases daily results were statistically analyzed. Average monthly precipitation, potential evapotranspiration and temperature time-series of the past were downscaled to daily based on stochastic disaggregation models. Aggregated (precipitation and potential evapotranspiration) or mean value (temperature) variables were disaggregated using simple techniques such as random models that follow the uniform distribution (Kozanis et al., 2010). The tool used for the abovementioned operations (disaggregation of time-series and calculation of *PET* based on the parametric model) was Hydrognomon v.4.1.0.26 developed by National Technical University of Athens (N.T.U.A.) and ITIA research team (http://www.itia.ntua.gr/en/softinfo/28/; Kozanis et al., 2010).

Unfortunately, it was not possible to include the spatial disaggregation of areal precipitation and temperature in the modelling, due to the small size of the catchment area of Spercheios River and the coarse resolution of the reconstructed time-series. Nevertheless, in order to include the influence of elevation on precipitation and surface temperature, lapse rates of Spercheios River Basin were applied (precipitation lapse rate: 9.79%/100 m based on Koutsoyiannis et al. (2003); temperature lapse rate: −0.54 °C based on Psomiadis (2010)).

2.3.3. Land use spatial distribution

The History Database of the Global Environment (HYDE) v.3.2, developed by the Netherlands Environmental Assessment Agency was used for the estimation of the long-term spatial alterations regarding agricultural activities at Spercheios River Basin. In HYDE historical population, cropland and pasture statistics are combined with satellite information and specific allocation algorithms (changing over time) to create spatially explicit maps, which are fully consistent at a 5′ longitude/latitude grid resolution, and cover the period 10,000 BCE to 2000 CE (Klein Goldewijk, 2001; Klein Goldewijk et al., 2011).

For the more recent periods 1960–90 and 2008–16, the main land use classes (irrigated, non-irrigated areas, transitional areas from bush lands to forest lands, mixed forest, artificial/no vegetated areas) were mapped based on the CORINE 2012 database (European Environmental Agency, 2012) and on the official agricultural census surveys (years 1929, 1950 and 2010, National Statistical Service of Greece) while irrigation demand was estimated by Mentzafou et al. (2017) and was spatially distributed per municipality.

2.3.4. Hydrographic network

The long-term natural shoreline and hydromorphological changes during the period 1660/61–1900/01 in Spercheios River Basin were not included in the hydrological model of the area, due to the relatively coarse spatial resolution of the model (400 m cell size) which does not allow small shoreline alterations to be simulated and furthermore, the most important and humanly imposed hydromorphologic alterations due to significant water management infrastructure took place during the period 1900–1960. For the periods 1960/61–1989/90 and 2008–2016 all completed engineering interventions that could affect the hydrological conditions were considered in the relevant simulations.

2.4. Statistical analysis

For identifying approximate changes in trends along time, the following three methods were used: a) the sequential version of the Mann-Kendall (SMK) test (Sneyers, 1990), b) the non-parametric rank-based, distribution-free CUSUM test (McGilchrist and Woodyer, 1975), and c) the sequential regime shift detection method (SRSD) (Rodionov, 2004). The first two were manually performed, while the third was performed through the excel add-in Sequential Regime Shift Detection (SRSD), version 3.4, which can detect statistically significant shifts in the mean level and the magnitude of fluctuations in the time series with the regime shift index (RSI) (Rodionov, 2004).

The sequential version of the Mann-Kendall test is calculated so that rank $(x_i) >$ rank (x_j) $(i > j)$. The t statistic is calculated as: $t = \sum_{i=1}^{n} n_i$. The distribution of t is assumed to be asymptotically normal with the following expectation: $E(t) = \mu = \frac{n(n-1)}{4}$ and $Var(t) = \sigma^2 = \frac{n(n-1)(2n+5)}{72}$. The null hypothesis that there is no trend is rejected for high values of the reduced variable |u(t)|, which is calculated as: $u(t) = \frac{t-E(t)}{\sqrt{Var(t)}}$. The statistic u′(t) is computed backwards starting from the end of the time series (Sneyers, 1990).

In CUSUM test, the test statistic *Vk* is defined as: $V_k = \sum_{i=1}^{k} sgn(x_i - x_{median})$, k = 1,2, …,n, where x_{median} the median value of the x_i data set and sgn(x) (McGilchrist and Woodyer, 1975).

The regime shift index (RSI) represents a cumulative sum of normalised anomalies of the time-series values from the hypothetical mean level for the new regime: $RSI_{i,j} = \sum_{i=j}^{j+m} \frac{x_i^*}{l\sigma_l}, m = 0, 1, \dots, l-1$ (i.e. number of years since the start of a new regime), *l* being the cut-off length of the regimes to be tested, and σ^l is the average standard deviation for all one-year intervals in the time-series. This is the level for which the difference with the mean level for the previous regime is statistically significant according to Student's *t*-test. If the RSI remains positive during a time period equal to the cut-off length, a shift is declared. (Rodionov, 2004).

The comparison between the hydrological cycle components under natural condition (1660/61–1900/01) and after human intervention (1960/61–1989/90) was based on the moving statistics method. In moving statistics, average, median and standard deviation are calculated for a sliding window, (in this case of 30 years), in order to identify the long-term changes of the period 1660/61–1900/01 and compare them with the statistics of the 30 years 1960/61–1989/90 period.

3. Results

3.1. Climatological data

The historical fluctuations of both annual temperature and precipitation during the entire study period (1660–1990) are highly varying at an intra-annual basis but after the year 1910 seem to become higher than in the past (Fig. 3). The 10-years moving average trendline indicate a maximum for the entire period regarding mean annual temperature in the year 1930 and an absolute minimum for annual precipitation in the year 1974. The 3 lowest peaks of annual precipitation during 1660–1990 are observed after the year 1907 while the warmest period was observed from 1920 to 1960 when the mean annual temperature was constantly above the long-term average of the entire study period (Fig. 2).

Comparing the climatological data of the reconstructed precipitation and temperature time-series and the respective dataset from the meteorological station of Lamia, a good agreement has been revealed which accredits the suitability of the reconstructed climatic data for the purpose of the study (Table 1). Especially in the case of temperature, the compatibility is very high ($R = 0.864$), while in both cases the result is significant at $p < 0.05$. Concerning the precipitation data, the negative value of the *PBIAS* indicates underestimation bias of the reconstructed time-series in relation to the Lamia station dataset. However, the correlation coefficient between the data series is again high ($R = 0.776$) and the *ME* is also relatively low.

Therefore, the reconstructed time-series describes well the natural variability of the observed climatological conditions, at least for the available common period of the two datasets (1970–1998).

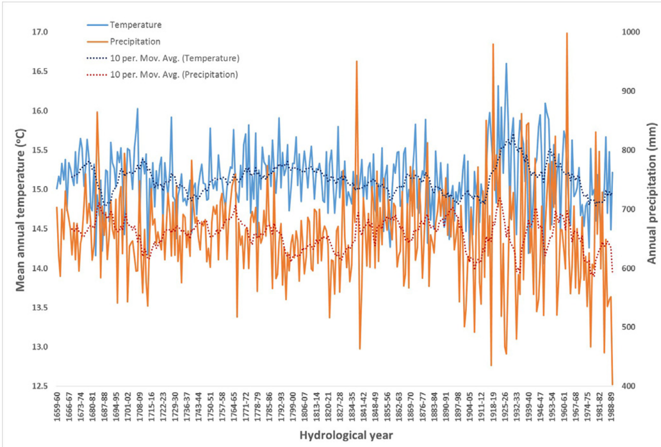

Fig. 2. Mean annual temperature and annual precipitation reconstructions at Spercheios River Basin.

Nevertheless, the different temporal scales of the climatic data series prior to 1960 and after 2008 did not allow for comparisons between the respective hydrologic model outputs.

3.2. Historical land cover trends

The total cropland area in Spercheios River Basin has increased by almost 190% during the period 1600–1900, while for the period 1600–2010, an approximate 355% increase is noted. Nevertheless, the last 40 years, 8% decrease in agricultural activities is observed (Fig. 3a). Based on the Census of Agricultural and Livestock Holdings of 2010, the agricultural activities in Spercheios River Basin in 2010 were 343 km^2, while according to HYDE the total cropland area was 341 km^2 during the same period which confirms the good performance and the applicability of HYDE data in the specific region.

The area's historical documentations, HYDE outputs and old maps, indicate that from 1600 until 1900 mainly the coastal and some lowland riverine areas were only cultivated in the specific basin. The relevant, official agriculture census conducted by Greek authorities, indicated that approximately 14% and 18% of the total cultivated land was irrigated in this province, in 1929 (Ministry of National Economy, General Statistics Service of Greece, Section B', 1934) and in 1950 (National Statistical Service of Greece, 1958) respectively, while in 2009 the irrigated areas reached 44% of the total cropland (Census of Agricultural and Livestock Holdings 2010; Hellenic Statistical Authority, 2014). Therefore, the agricultural activities in the past and until 1900 consisted of mainly non-irrigated crops. Based on the above information, the spatial distribution of the cultivated, non-irrigated areas at Spercheios River was mapped and used as input in the hydrologic model while the rest of the area was considered to be covered by mixed forest (Fig. 3b).

3.3. Historical trends of hydrological cycle components

SMK and CUSUM tests (Fig. 4) and SRSD (Fig. 5) identified various trends at the 1% significance level of the main hydrological cycle components. Considering the trend variability on decadal to multi-decadal time scales the precipitation and evapotranspiration follow similar patterns with an increasing trend from 1660 to 1700, followed by a small recession and a gradual increase that gets higher after 1740 until 1770. Then a relatively stable period followed until approximately 1790 when a persistent decreasing trend was observed, reaching the lowest point in 1840. In the next 60 years the observed trends were increasing for both precipitation and evapotranspiration and a strong recession followed in the recent study period (1960–1990). The overland flow and storage change illustrate a similar behavior to the precipitation and evapotranspiration as expected but with much less pronounced slopes in the identified trends. For the overland flow the statistically significant trend was the decrease over the period 1790–1840 while for the storage change two major trends are distinctive (increase in 1660–1770 and decrease in 1790–1900). In the recent period (after 1900) the overland flow illustrates a slight increase even though precipitation decreases which can be attributed to the land use changes that were significant during this period, including deforestation for agricultural or urban development purposes.

The moving statistics charts confirm the previous findings, since they present similar fluctuations of the hydrometeorologic parameters over the same periods of time (Fig. 6). The variability in precipitation is higher in the recent years than in the past (prior to 1840) while the decrease of precipitation in the years from 1960/61 to 1989/90 becomes apparent. During the period 1850–1880 an extensive dry period was observed while after 1890 the overland flow increased and fluctuated at the second highest levels of the last 300 years (the highest being in 1670–1700). Nevertheless, the moving average of the period 1960–1990 is slightly lower than the long-term average and median of the entire study period. The actual evapotranspiration illustrated two periods with very high levels (1740–1770 and 1810–1830) while during the period 1960/61–1989/90 was slightly decreased compared to the past but laying still at higher levels than the long-term average (Fig. 6). Groundwater storage illustrate almost identical patterns to the evapotranspiration, with a relatively low decline in the recent years (after 1960) at levels though that are very close to the long-term average and median of this parameter. The relatively high levels of evapotranspiration after 1900, with the simultaneous decline in groundwater storage and overland flow can be attributed to the corresponding increase of agricultural activities that led to the decrease of

Table 1
Statistical comparison between the different climatological time-series.

Time-series 1	Time-series 2	Parameter	Period	N	ME	MAE	RMSE	STDres	R	PBIAS
SO&P	Lamia	Precipitation	1970–1998	347	3.228	20.056	27.960	785.275	0.776*	−7%
SO&P	Lamia	Temperature	1970–1990	250	−1.635	3.340	4.004	113.636	0.864*	10%

N sample size.
ME mean error.
MAE mean absolute error.
RMSE root mean squared error.
STDres standard deviation of the residuals.
R correlation coefficient.
PBIAS percent bias.
* The p-value is <0.00001. The result is significant at $p < 0.05$.

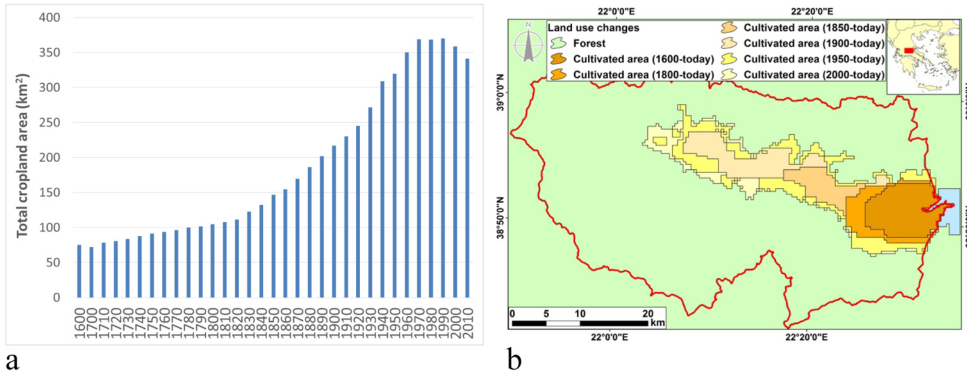

Fig. 3. (a) Long-term change of total cropland area based on HYDE, and (b) long-term spatial distribution of cultivated areas in Spercheios River Basin.

natural vegetation and forests and to the aforementioned hydrologic changes (Fig. 6).

Concerning the outflows of Spercheios River to Maliakos Gulf on a monthly basis, the average discharge varies considerably throughout each year. During the wet period of each year (October to March) the modeled outflow is almost identical for the periods 1660–1900 and 1960–1990 while during the summer period (April to September) there is a significant decrease in the outflows to Maliakos Gulf in the period 1960–1990, compared to the past (Fig. 7). This is mainly the result of the water abstractions for irrigation that during 1960–1990 increased significantly in relation to the past due to the large scale hydraulic infrastructure that were constructed in the area in the early 60s.

Moreover, high discharge levels were spread in larger part of the year in the beginning of the study period while in the period 1960–1990, most of the annual discharge is observed during January and February (Fig. 7). March is the month that illustrates the highest losses of discharge along time in the study period, followed by December.

Monthly discharge of Spercheios Rivers to Maliakos Gulf varies considerably throughout the different study periods (Fig. 8). During the period 1660/61–1900/01 the annual median discharge was 9.79 m^3/s and the intra-monthly variations were relatively small (Fig. 7) while during 1960/61–1989/90 the discharge was considerably smaller (median: 6.22 m^3/s) and the discharge variations within each month were significantly higher than in the past (especially during the winter period). These variations together with the number of outliers and extremes per decade which are higher in the recent period in relation to the past, imply a more stable hydrometeorologic behaviour of the catchment in the past relatively to 1960/61–1989/90. During summer, in the 1960/61–1900/01 the median monthly values were considerably higher than during 1960/61–1989/90, which indicates the important impacts of water abstractions that occur mainly from April to September in the study area. However, even before the period of human impacts on water resources, the seasonality effect in the discharge is very distinctive in the area (very low discharge values in the summer compared to the winter ones).

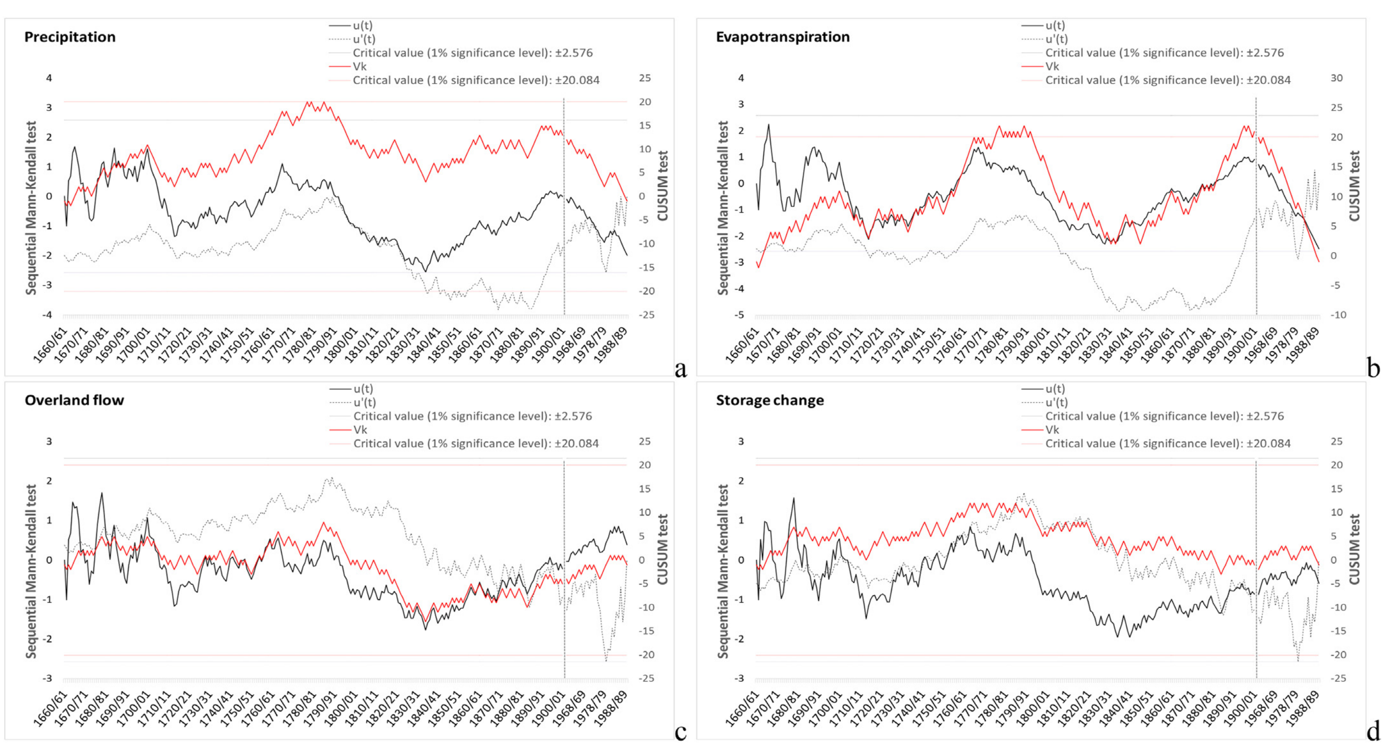

Fig. 4. SMK and CUSUM tests for (a) precipitation, (b) evapotranspiration, (c) for overland flow, and (d) for change of storage.

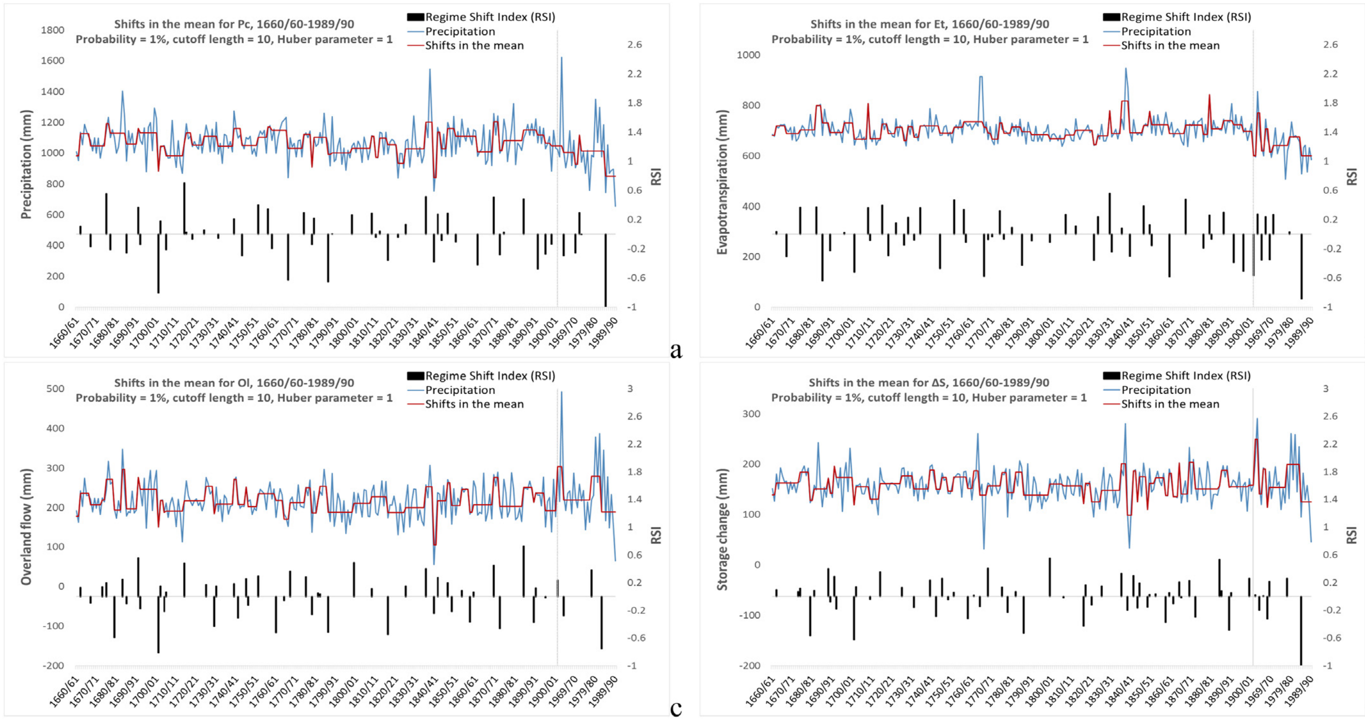

Fig. 5. SRSD test for (a) precipitation, (b) evapotranspiration, (c) for overland flow, and (d) for change of storage.

In terms of water budget at the catchment scale, the long-term average and median precipitation, evapotranspiration and snow storage change were higher in the 1660–1990 period in relation to the 1960–1990 period (Table 2). On the contrary, groundwater storage change, overland flow and irrigation are higher in the recent period. This pattern is the result of a combination of land use changes occurred in the early 20th century (transformation of forests to agricultural land and urban areas) and water management practices such as abstractions for irrigation. The particular land use changes created higher overland flow levels due to the increase of impermeable surfaces which however

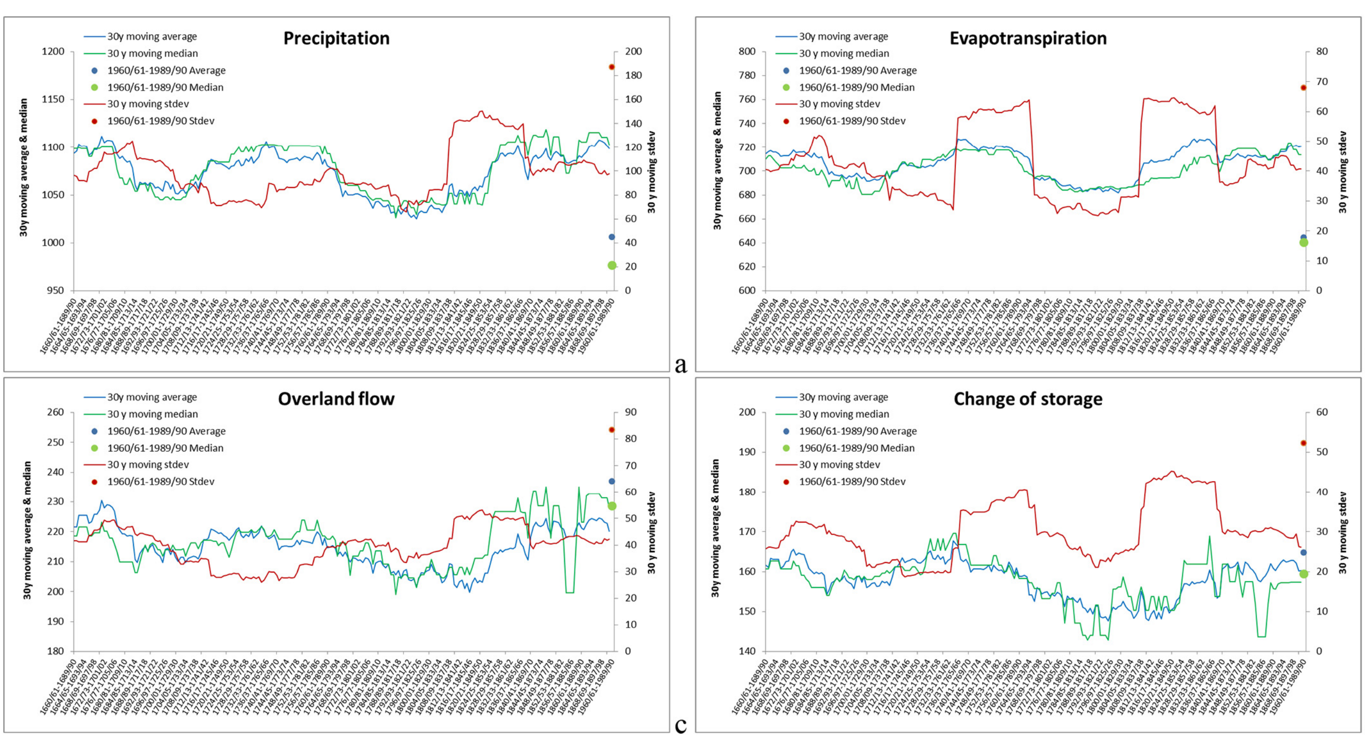

Fig. 6. 30-years moving statistics for (a) precipitation, (b) evapotranspiration, (c) overland flow, and (d) change of storage for the period 1660/61–1900/01 compared to average monthly discharge for the period 1960/61–1989/90.

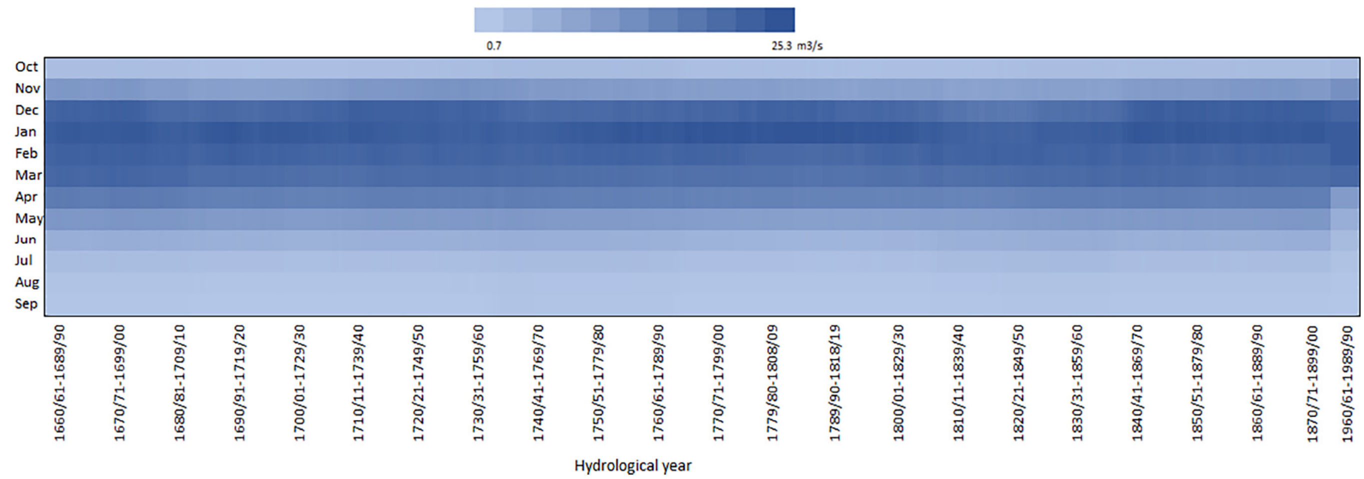

Fig. 7. 30-years moving average of monthly discharge (m^3/s) of Spercheios River to Maliakos Gulf for the period 1660/61–1900/01 compared to average monthly discharge for the period 1960/61–1989/90.

was not transformed to higher outflows to Maliakos Gulf from Spercheios River due to the water consumption for irrigation (most of the relevant infrastructure was built from 1930 to 1960 in the area). The reduction of natural vegetation slightly decreased the evapotranspiration while a relatively small increase in temperature led to the reduction of snow storage in the recent period (Table 2). The irrigation for the period of 1960–1990 was approximately 3.4% of precipitation while before 1900 water abstractions for irrigation were negligible due to the lack of appropriate infrastructure and the existence of a non-commercial farming system.

4. Conclusions and discussion

Climate and climatic parameters (such as precipitation and air temperature) variability, can arise from a number of forcing factors, some external (e.g., solar irradiance or volcanic activity) and others internal (e.g., atmospheric chemistry) to the climate system (Bradley, 2015). The effect of each forcing factor to the hydrological cycle of an area although undisputable, cannot be easily quantified. This is even more important on the regional scale, because here a combination of site-specific effects like atmospheric circulation and the impact of humans are getting more important compared to continental, hemispheric or even global scales. It is estimated that pre-industrial (pre-1850) temperature variations were mainly due to changes in solar irradiance and volcanism (Crowley, 2000). It is argued that the solar influence since 1900 in the industrial age has become an increasingly less significant component of climate change (Lean and Rind, 1999). Greece is a highly volcanic and seismic area due to its location relevant to the Euro-Asiatic lithospheric plate boundary and therefore has been strongly affected by volcanic and seismic activities in the past (Nomikou et al., 2012; Pyle and Elliott, 2006).

Some commonly known periods during which climate events took place due to various reasons might be identified in the study area. The 1714/15 trend change from decrease to increase for all hydrological cycle components might be influenced by a combination of low solar activity and increased volcanic activity, which is also known as Maunder Minimum and during which Europe and North America experienced in general colder than average temperatures (Eddy, 1976). In this

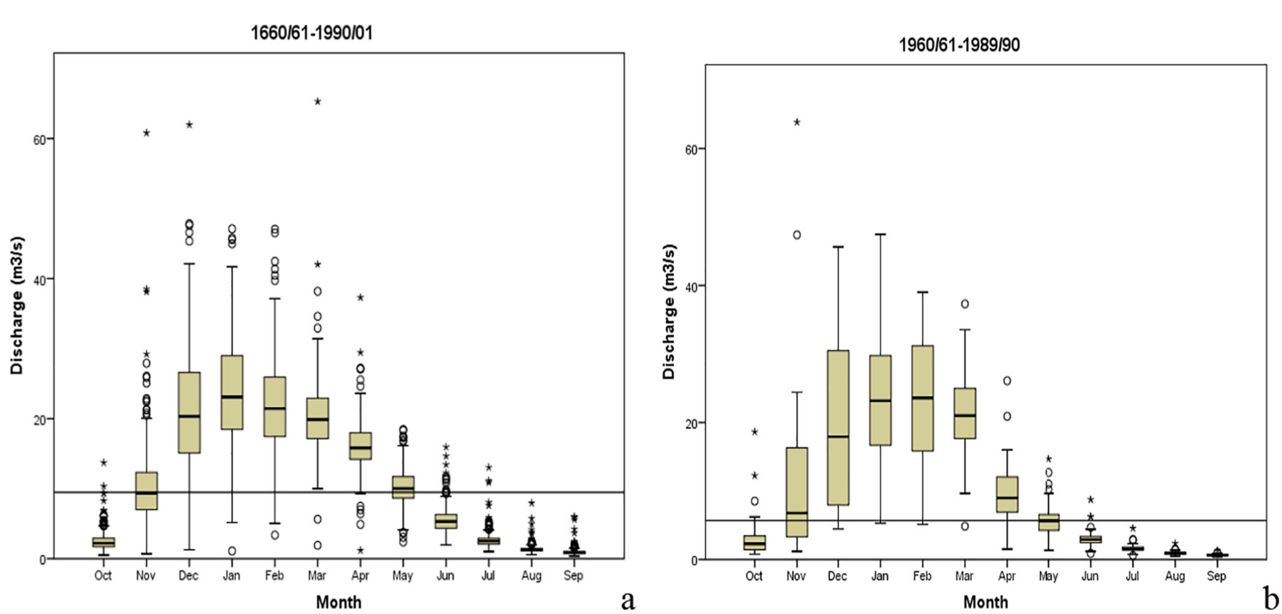

Fig. 8. Box-plots of monthly discharge of Spercheios River to Maliakos Gulf: (a) 1660/61–1900/01, (b) 1960/61–1989/90, (black line: median).

Table 2
Water budget of Spercheios River Basin for different periods, with and without water management project.

		1660/61–1900/01		1960/61–1989/90	
		Average	Median	Average	Median
Precipitation	mm	1075.1	1077.22	1006	976.77
Evapotranspiration	mm	707.3	702.32	644.3	640.51
	%	65.80%	65.20%	64.00%	65.57%
Overland flow	mm	215.5	215.46	237	225.69
	%	20%	20%	23.60%	23%
Inflows from or outflows to neighboring basins	mm	−25.8	−25.91	−22.3	−22.23
	%	−2.40%	−2.41%	−2.20%	−2.28%
Storage change	mm	158.2	158.44	164.7	159.35
	%	14.70%	14.71%	16.40%	16.31%
Snow storage change	mm	20	18.51	16.2	14.04
	%	1.90%	1.72%	1.61%	1.44%
Irrigation	mm	–		−33.9	−33.13
	%	–		−3.37%	−3.39%

trend the significant volcanic eruption which occurred in 1650, close to Santorini island, may have contributed since the specific event has been characterized as the most important during the last millennium in Eastern Mediterranean (Druitt et al., 1989).

Other shift changes detected might be linked to large tropical volcanic eruptions. While effects of volcanic eruptions on temperature are well studied (Robock, 2000; Timmreck, 2012), the effects of volcanic eruptions on the water cycle and precipitation is less known (Wegmann et al., 2014; Iles and Hegerl, 2015). The 1786/87 trend change from increase to decrease for precipitation, overland flow and storage change may be associated to the 1783–84 eruptions in Laki, South Iceland (Thordarson and Self, 2003). The 1816/17 trend change (from increase to decrease) of precipitation could be attributed to the volcanic eruption in Tambora, Indonesia in April 1815, since rainfall was anomalously high across most of Europe except the eastern Mediterranean during the summer of 1816 (Oppenheimer, 2003). Compared to the Laki eruption the Tambora eruption was most likely one of the largest in past millennium with global impacts on both, temperature and precipitation. On the other hand, in January 1835 an eruption that took place in Cosiguina, Nicaragua that may be responsible for the trend change in 1835/36 for all hydrological cycle components from decrease to increase, which is in agreement with the increase of south-central European summer precipitation in the year following the volcanic eruption found by Wegmann et al. (2014). The trend change in 1884/85 from decrease to increase for precipitation and some later trend changes in the late 19th and 20th century might also be linked to the volcanic eruption, for instance in Krakatoa, Indonesia in 1883 and/or Santorini – Greece in 1866–70 (Pyle and Elliott, 2006). The 1963/64 or 1964/65 trend change from increase to decrease can be attributed to Agung, Indonesia volcanic eruption in 1963. Finally, the 1984/85 trend change of precipitation and evapotranspiration from increase to decrease coincide with the volcanic eruption in El Chichon, Mexico in 1982. Moreover, the low precipitation rate during the period 1960/61–1989/90 can be attributed to the intensively dry periods at the end of the 80s.

Another important factor that affected the long-term changes of the hydrological cycle components of Spercheios River Basin is land use changes and especially deforestation that has taken place in the area. Since 1600 cropland area has increased up to 355% from 75 to 341 km^2, leading to loss of natural vegetation. The large-scale irrigation infrastructure has been constructed between 1930 and 1960 which included an extensive network of canals that distributed water in the lowland areas of the catchment. The agricultural production progressively shifted towards a commercial type which increased water consumption and decreased the water availability and the outflows to Maliakos Gulf. The average irrigation demands from 1960 to 1990 reached approximately 3.5% of the annual precipitation while in the last 20 years this figure has been further increased (Mentzafou et al., 2017). The natural vegetation areas were continuously shrinking in the catchment while urban and impermeable areas have been increased since 1900, which caused slight reduction in evapotranspiration and increase in overland flow. Human interventions and activities have intensified these trends considerably, especially through irrigation during the dry period each year (April to September), when large amount of water is directed towards the cropland, without considering the resource availability which increases the impacts in the riverine ecosystem (Mentzafou et al., 2015). The relatively low precipitation levels observed in 1960–1990 in relation to the prior to 1900 period and the slightly higher recent air temperatures may be responsible for the reduced snow storage capacity in the recent period but almost all the rest hydrologic alterations mentioned above should be attributed to anthropogenic land use and water management practices. Climate change is another factor that can strongly affect the hydrologic regime of an agricultural river catchment such as Spercheios and therefore urgent mitigation actions should be undertaken, at a local and regional levels, to eliminate these combined pressures which otherwise may cause irreversible hydromorphologic alterations in the riverine systems.

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